

Arp 102B: An ADAF and a Torus?

Ranga-Ram Chary

Spitzer Science Center, MS220-6, Caltech, Pasadena, CA 91125

Abstract.

Arp 102B is a nearby radio galaxy which displays the presence of double-peaked Balmer emission lines. Sub-arcsec Keck mid-infrared imaging and *Spitzer* spectroscopy reveal a spatially compact mid-infrared source which displays tentative evidence for variability. The $F_\nu \propto \nu^{-1.2}$ spectral energy distribution is suggestive of an advection-dominated accretion flow. The absence of dust features over the 5–40 μm range make it unlikely that thermal dust emission dominates the mid-infrared luminosity. We also detect the presence of molecular hydrogen in emission which is asymmetrically redshifted by $\sim 500\text{--}1000$ km/s from the systemic velocity of the galaxy. Since the forbidden, low-ionization lines in this galaxy are at the systemic velocity, we suggest that the molecular hydrogen emission arises from a rotating molecular gas structure surrounding the nuclear black hole at a distance of ~ 1 pc.

1. Introduction

Arp 102B is an E0, radio-loud galaxy at a distance of 104.9 Mpc (Eracleous & Halpern 2004). Stellar dynamical measurements indicate a velocity dispersion of 188 ± 8 km s $^{-1}$ (Barth et al. 2002), which implies a black hole mass of $\sim 10^8 M_\odot$ (see also Newman et al. 1997). The AGN in Arp 102B is of the “double-peaked” emitter class. The simplest possible explanation for this spectral profile identifies an accretion disk as the source of these lines. The AGN also shows strong low-ionization lines and very weak/absent high-ionization lines (Stauffer et al. 1983; Halpern et al. 1996). The weakness of the high-ionization lines and absence of double-peaked structure in them supports the accretion disk origin under the assumption that the outer parts of the thin disk are invisible to the photoionizing source. The absence of a strong UV bump, presence of a hard X-ray source and low Eddington luminosity of this object are indicative of an advection-dominated flow (ADAF; Ho et al. 2000).

In this paper, we present the results from high-spatial resolution mid-infrared imaging and moderate resolution infrared spectroscopy of the nucleus of Arp 102B. Mid-infrared fine structure emission lines (e.g., [Ne II], [Ne III], [O IV]) are less affected by extinction and help determine if shocks or photoionization are responsible for the line excitation mechanism. The mid-infrared is also the regime of molecular H $_2$ rotational lines which provide an independent measure of temperature and mass of the surrounding gas.

2. Broad-band Properties

In the Keck/LWS observations undertaken in 2000, the AGN in Arp 102B was found to have a flux density of 90 ± 20 mJy at $12.5 \mu\text{m}$. The source was undetected at $17.9 \mu\text{m}$ with a 3σ flux density limit of 50 mJy. In the *Spitzer* observations in 2005, the source has decreased in brightness by more than a factor of 2 at $12 \mu\text{m}$ since the Keck observations and has shown a change in the infrared spectral energy distribution (Figure 1). The *Spitzer* measurements are also consistent with the Puschell et al. (1986) value of 23 ± 7 mJy derived from $10.6 \mu\text{m}$ observations made in 1981. As a result, it is unclear if the Keck data suffer from photometric calibration errors or if there actually is a factor of ~ 2 variability in the brightness of the source.

The broad-band flux density in the *Spitzer* data can be best represented by the form $F_\nu(\text{mJy}) = 1.7 \times \lambda^{1.23 \pm 0.15}$ with evidence for a turnover at $\lambda > 20 \mu\text{m}$. Such a spectrum is remarkably similar to that observed in NGC 4258 (Chary et al. 2000) where the emission was thought to arise from self-Comptonized synchrotron radiation. The $5\text{--}40 \mu\text{m}$ luminosity of the source is $6.7 \times 10^9 L_\odot$, which is comparable to the $0.2\text{--}10$ keV luminosity measured by *ROSAT* and *ASCA* in 1991 and 1998, respectively (Eracleous et al. 2003). The bolometric luminosity derived by integrating over the full SED including the radio/millimeter measurements by Puschell et al. (1986) is $8 \times 10^{43} \text{ ergs s}^{-1}$. This implies that the Eddington ratio of the $10^8 M_\odot$ black hole is $\sim 6 \times 10^{-3}$, about 5 times larger than previous estimates and marginally within the ADAF limit.

3. Emission-line Properties

3.1. Low-ionization Lines

Figure 2 shows the emission lines that are detected in the spectrum of Arp 102B. As noted from optical/UV spectroscopy, the spectrum of Arp 102B is dominated by low-ionization metallic fine structure lines with a notable absence of high-ionization lines. [O IV], which has an ionization potential of 55 eV, is the most prominent of these features but is known to exist in starburst galaxies. Adopting the simplified model of Sturm et al. (2002), the [O IV]/[Ne II] ratio of 0.21 ± 0.05 and absence of high-ionization lines would indicate that that 90% of the bolometric luminosity in Arp 102B is powered by a starburst. The measured [Fe II]/[O IV] ratio of 0.86 ± 0.25 is also remarkably similar to that of NGC 6240, which is thought to be a starburst-dominated source (Lutz et al. 2003).

However, Arp 102B shows an absence of strong polycyclic aromatic hydrocarbon dust emission or silicate features. PAHs are commonly thought to be present in starbursts. It is unclear if the PAHs are absent because they are destroyed in the hard radiation field around an AGN/super starburst or because there is no dust in the vicinity of the AGN. The latter is a less likely option given the presence of molecular gas emission in the infrared spectrum.

With a [Ne II]/[S III] ratio of 2.3 ± 0.5 and [Ne III]/[Ar II] > 3.1 , Arp 102B is out of the starburst-powered regime and intermediate between the shock-excited and photoionization-excited regimes. The pure photoionization models in Spinoglio & Malkan (1992) reproduce the observed [Ne III]/[O III] $\lambda 5007$ ratios very well but underestimate the [Ne II]/[Ne III] ratio. Ionizing shocks from starbursts

and supernova remnants, can account for the observed $[\text{Fe II}]/[\text{O IV}]$ ratio as well as the high $[\text{Ne II}]$ line flux. Thus, we conclude that the low-ionization line spectrum of Arp 102B is a composite, dominated by photoionization but with $\sim 20\text{--}30\%$ contribution from slow shocks.

3.2. Molecular Hydrogen Emission

One of the striking features of the spectrum are the S1 and S3 rotational lines of H_2 , which appear to be offset in velocity from the systemic velocity of the galaxy. The ratio of the S(3)/S(1) line fluxes is 1.6, indicative of warm molecular gas at a temperature of ~ 400 K. None of the other H_2 lines are detected. Although the forbidden lines are observed at the systemic velocity of the galaxy, the H_2 lines are offset by $> 2\sigma$ at both the orders. This is unlikely to be due to wavelength calibration uncertainties. We suggest that the molecular hydrogen might be in a rotating molecular gas structure with the redshifted emission stronger than the blueshifted emission due to a warp. We do not detect the blueshifted emission of the S(3) line because of inadequate wavelength coverage in the spectrum. The size of the structure is about ~ 1 pc, ranging from 0.5–2.7 pc depending on the adopted velocity range.

Although the mid-infrared lines are offset, the near-infrared H_2 lines in ground-based spectra appear to be at the systemic velocity of the galaxy (Rodríguez-Ardila et al. 2005). This is surprising. One possibility is that the near-infrared continuum and line emission are being dominated by the starlight while the mid-infrared is being dominated by the region around the AGN. Furthermore, the strength of the near-infrared lines is far too strong for the gas temperature that we derive from the ratio of the mid-IR H_2 lines. Thus, unless there are unknown wavelength calibration uncertainties in the mid-IR spectrum, there must be a hotter gas component which dominates the near-IR molecular gas emission.

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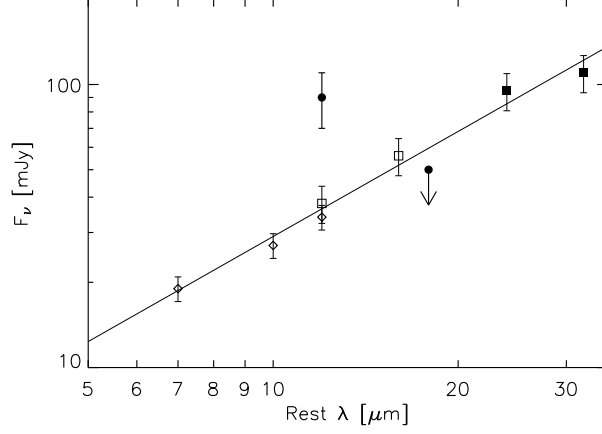


Figure 1. Infrared spectral energy distribution of Arp 102B from *Spitzer* 2005 data and Keck 2000 data (solid circles). The luminosity of the nuclear source has decreased by a factor of 2.5 at 12 μm between the Keck and *Spitzer* observations while its spectral shape has inverted, suggestive of a transition from a thin disk to an ADAF. However, calibration uncertainties are a possible source of error for the Keck data.

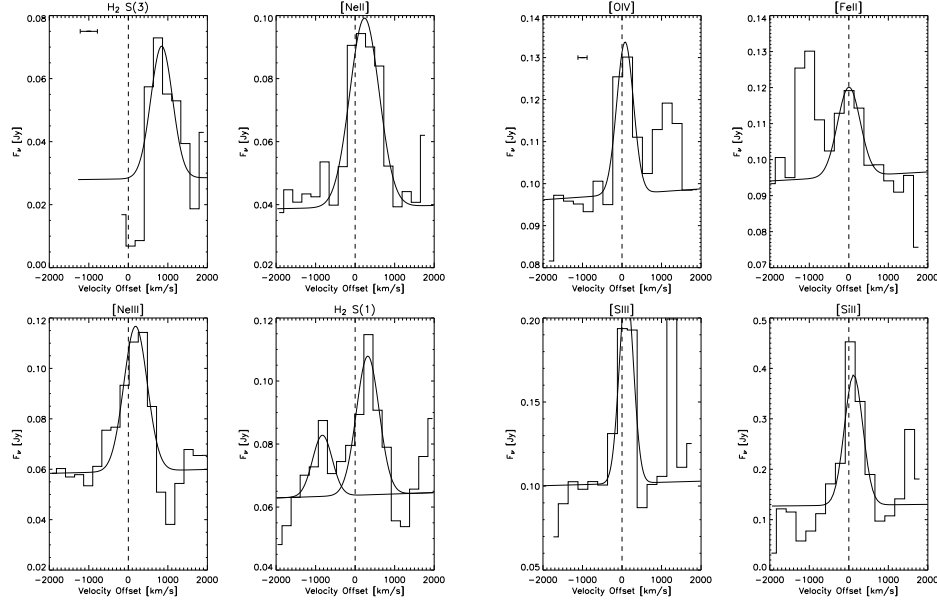


Figure 2. Spectral lines seen in the *Spitzer*/IRS spectra with a best-fit Gaussian and constant baseline. Also shown is the $\pm 1\sigma$ uncertainty in the wavelength calibration for the SH and LH modules. Although the forbidden lines are consistent with no velocity offset to within the calibration uncertainty, the H_2 lines are offset by 500–1000 km s^{-1} from the systemic velocity. Given the mass of the black hole, it implies the molecular hydrogen is ~ 1 pc from the nucleus.